

Argon Power Cycle Workshop  
University of California, Berkeley  
August 2, 2014

Systems Engineering Approach to Zero  
Carbon Emission Grid: Variable  
Generators, Storage, Back-Up,  
Electricity Cost Trends

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INCOSE-CC

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***INCOSE-CC*** is a Professional Organization,  
International Council on Systems Engineering-  
Chesapeake Chapter, Maryland.

***John Rudesill***: ChE 32 yrs at Grace Refining Catalysts  
manufacturing, R&D materials science.

Semi-retired, teach senior elective Chemical Process Development  
at UMBC. Have life long interest in engines and energy conversion  
processes. Advised MS grad student Ben D'Alessio on project to  
demonstrate a process to reduce energy consumed to distill and  
dehydrate ethanol that lead to contact with Prof. Dibble 2010  
regarding his work with HCCI.

***Systems Engineering*** is a professional discipline that focuses on efficient project management, is interdisciplinary, and seeks to be technology neutral by emphasis on complete systems.

- 1. *State a goal*** in form of requirements—an outgrowth of US Gov. procurement procedures: What is to be accomplished, when, budget, etc. Can be flexible if requirements change.
- 2. *Assemble teams*** (bidders e.g.) to propose various concept scenarios to achieve goal e.g. Apollo space program.
- 3. *Review trade offs*** among scenarios eventually in an open and competitive “**critical review**” as opposed to literature peer review.
- 4. *Stakeholders decide*** from critical review which scenario they will fund.

*Future of Energy Initiative Working Group* was founded by Chairman Dr. Alex Pavlak also an adjunct at UMBC, myself, and Dr. Harry V Winsor as an ad hoc group.

*Our quest* is to bring the array of technologies advocated for clean, green, renewable, sustainable, etc. energy together for comparative “critical reviews” to *enable stake holders* to choose a path to safe, affordable, sustainable, truly clean energy that is driven by *overall best system* rather than advocacy for specific technologies.

Our effort is in its 3<sup>rd</sup> year working part time pro bono. We have grad students helping write papers. Three given this week at ASME Power Conference held in Baltimore. We meet weekly by Google Hangout. Nathan Smith won best student paper.

## *Renewable Goals:*

**20% by 2020, 40% by 2025, 30% by 2030, 80% by 2050, etc.**

**Lets look at ~100% by 2050 as our goal and consider a scenario with a high contribution from wind say 90-100%.**

**Let's use round numbers for raw preliminary scaling to see the magnitudes.**

**The next slide shows some typical plots of wind output versus load for the TX ERCOT system from 2012.**

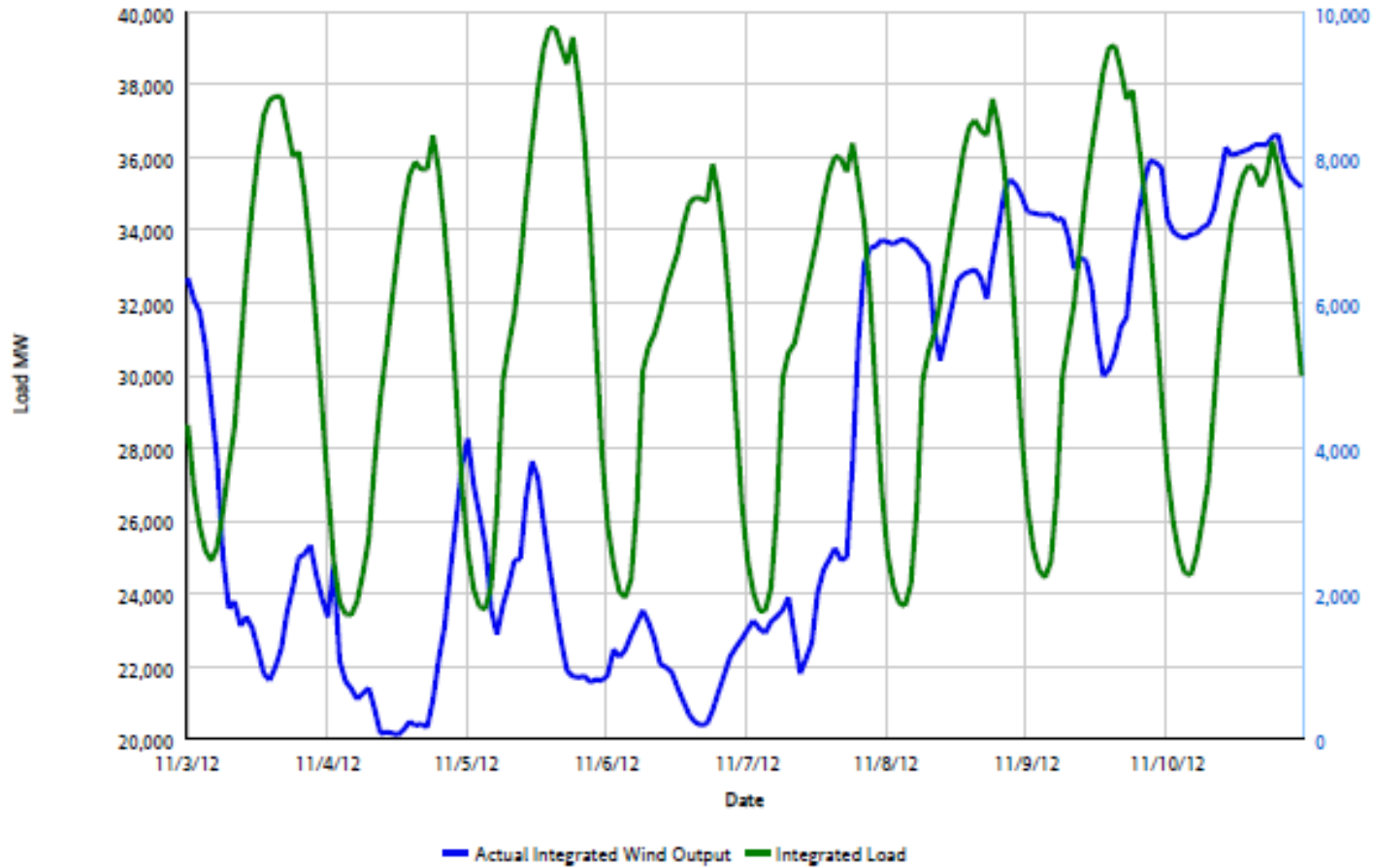
***What do we see?***

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ERCOT PUBLIC

WIND INTEGRATION REPORT

ERCOT Load vs. Actual Wind Output  
11/03/2012 - 11/10/2012



## *We See:*

1. Average load is ~30GW, peaks to ~39GW
2. Average wind is ~4GW.
3. We can estimate that ~8x current wind 32GW might meet average load at least some of the time.
4. Wind ~0GW for hrs at a time and very low for days and this occurs at almost the peak demand twice in one week!
5. There are times when the load is low and the wind is peaking. An 8x output would far exceed the load forcing large curtailment and lost wind productivity = higher \$/kwh.
6. Storage can help with this at a cost. The trade off is between lowered wind overbuild with less curtailment loss, and the cost of the storage subsystem.

## *Systems Engineering Obligates us to consider:*

1. The electric grid is a *sophisticated highly complex energy delivery system* built from many subsystems that all have to work well together to give economical, highly reliable, and high quality electricity.
2. *Traditional reliability for electric utilities is the worst day in 10 years—99.97%* per FERC & IEEE. SE looks at *worst case* for design requirements to meet reliability.
3. *Wind reliability* is based on the average of the *worst three days in three years (PJM)*. This is a very different and more lenient assessment. Limited data is usually given as the justification. *Is this acceptable?*



## *One day US Electric grid storage:*

1. One days US grid is on the order of 500GW average demand for 24 hrs = 12,000 GWhs! Peak demand is ~700GW.
2. The Bath, VA Pumped Hydro Storage (PHS) facility is the largest in world. It can provide 3GW for ~8 hrs (24GWhs) at 80% round trip efficiency. Recharge at night ~10 hrs 30GWhs.
3. Need >500x Bath PHS units to meet one day at average demand. Build 14 plants/yr through 2050. How to meet ~700GW peaks?
4. Bath size units might cost \$3 billion to build today leading to a \$1.5 trillion capital expense, but finding that many suitable sites in the US is unlikely.
5. The unit will deliver ~300,000GWH over a 40 yr life which is only ~1 cts/kwh capital. The 80% roundtrip efficiency will add ~2.5 cts/kwh on top of 10 cts/kwh input electricity.

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*Lets look at one day US Electric grid storage [Batteries]:*

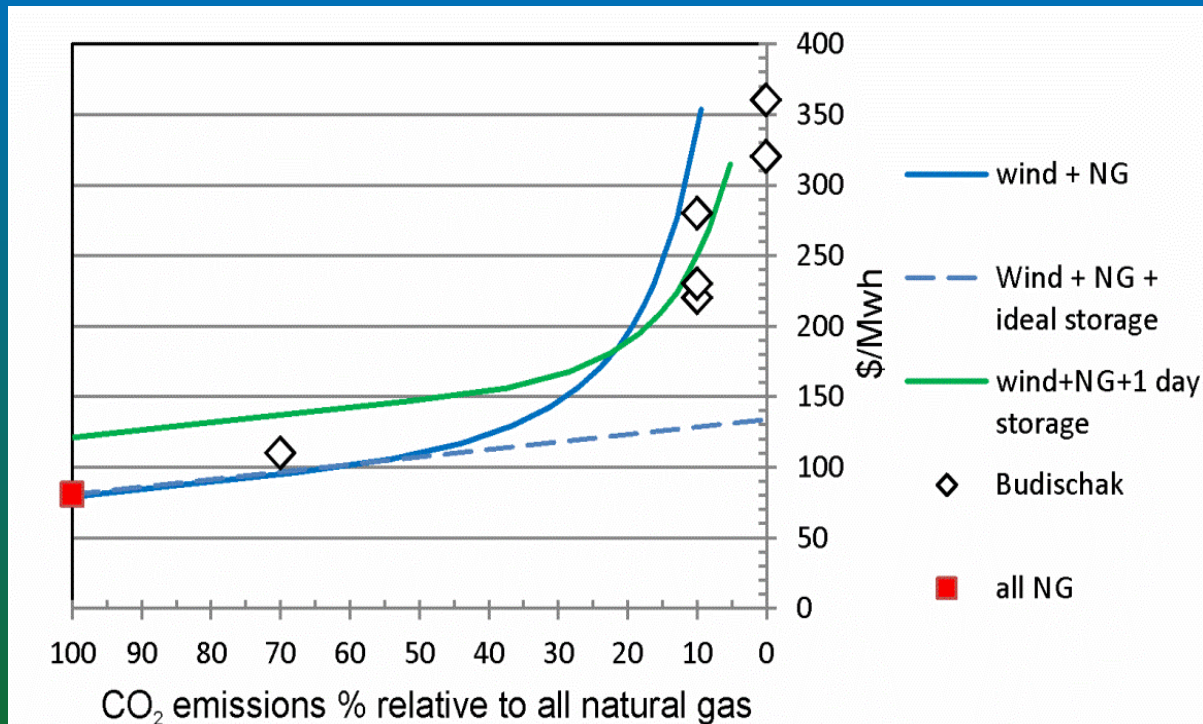
1. Batteries are developing fast. We often see only the power delivery rate in MW or GW, but not more meaningful GWh capacity. Complete system costs often not determined.
2. Consensus suggest batteries need to drop  $< \$100\text{kwh}$ . Many challenges to achieve this and scale to grid one day needs.
3. Battery metrics include:  *$\$/\text{kwh}$  capacity*, round trip efficiency, charge/discharge rate, depth of discharge, number of cycles before failure. A *cost  $\$/\text{kwh}$  delivered* can be computed by normalizing the  $\$/\text{kwh}$  capacity with the total energy input and delivered over its lifetime. It is subsystem add on to the cost of electricity delivered.

## *Argon Power Cycle at US Electric grid scale storage:*

1. Subsystem must include huge scale water electrolysis with gas storage for H<sub>2</sub> and O<sub>2</sub>
2. Typical water electrolysis is ~75% efficient and assume APC is ~75%, then electrolysis capacity has to be sized to handle most of peak wind production offset by low wind times.
3. One day storage will need H<sub>2</sub> from 21,300 GWH of electrolysis. Largest electrolysis units are ~1MW range so system will need at least >890,000 units. At ~\$1million each, we are at \$890 billion plus gas storage, etc.
4. If the “Iron Fuel Cell” is ~\$1000 kwh, need \$500 billion to meet average load and \$700 billion to meet peak.
5. The system cost is very roughly converging toward the PHS cost ~1.5 trillion without PHS siting limits. Similar 3.5 cts/kwh add on.

## *Wind + NG Grid, Penetration Vs CO<sub>2</sub> Reduction & \$/MWh*

Budischak, Kempton et al 99.9% Renewables paper 2013, in Goudarzi, Pavalak paper given at ASME Power Conference, Baltimore July 2014.



## ***Conclusions:***

- 1. “Iron Fuel Cell” Argon Power Cycle is an interesting and promising way to enable the very large energy storage needs of ~zero carbon emissions electric grid while maintaining reliability.**
- 2. The costs of such a system though large are inline with existing PHS storage and are more practical compared to the latter in terms of land use (\$40 billion/y through 2050).**
- 3. Formally applying a Systems Engineering approach toward renewable clean energy systems is in early stages and we welcome input from interested parties to help us compile and publish critical reviews of a full range of low carbon emission electric grid scenarios.**
- 4. Our web site with papers under “files” button is:  
<https://sites.google.com/site/futureofenergyinitiative/home>**

# To do

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- Transmission upgrades internal to the grid
- Congestion induced curtailment
- Multiple years
- Multiple regions
- Storage parameter variation
- Add solar PV
- EIA cost refinement

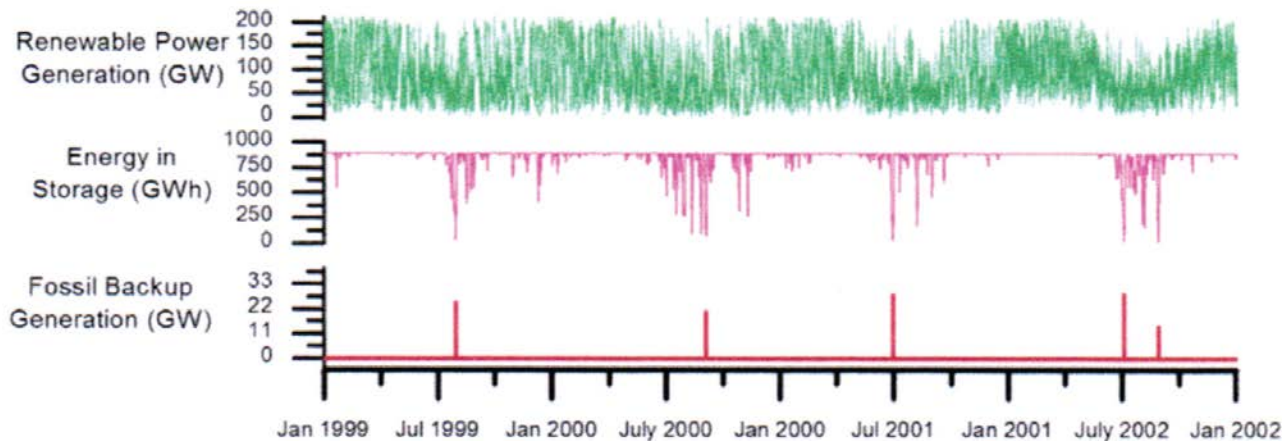
# Basis for system trades

- Top down, whole systems
- Focus on design drivers
  - Real load profile data
  - Real (scaled) wind profiles
  - Minimal detail
- No wind capacity credit
- EIA levelized cost estimates
  - New 2018 installations
  - Consistent set of cost assumptions

Generator technology	CF %	Fixed cost	Variable cost	Levelized cost
Advanced nuclear	90	96.1	12.3	108.4
NG adv. combined cycle	87	20.6	45	65.6
Geothermal electric	92	89.6	0	89.6
Wind – onshore	34	86.6	0	86.6

Table 1 Levelized cost components estimated by EIA (\$/MWh)

# Wind + fossil fuel + storage\*



Load was met with renewable generation and storage 99.9% of hours over 4 years; fossil backup needed on five occasions

\* Budischak, et al, Cost minimized combinations of wind, solar, storage, *Journal of Power Sources* 225, 2013, pp. 60-74

## Paper summary

- 0.1% fossil fuel system for PJM region appears to be technically feasible
- 3x wind energy overbuild, discard 2/3 of electricity
- ~ 24 hours storage
- Fossil fuel backup ~8 hrs/yr
- Stated cost ~ 38¢/kWh

## Critique

- Extreme events (July) drive system size
- \$0.38/kWh cost estimate is optimistic (>\$0.67/kWh)
- Large environmental impact ~24,000 sq miles, the size of West Virginia
- Concept is sound but needs classical concept development